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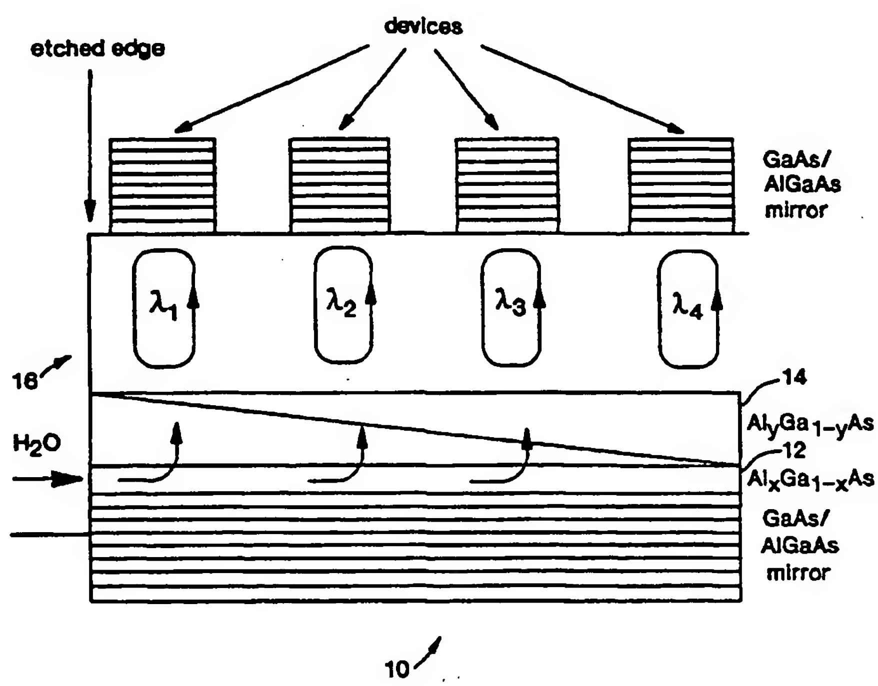
(54) Title: POSTGROWTH ADJUSTMENT OF CAVITY SPECTRUM FOR SEMICONDUCTOR LASERS AND DETECTORS

(57) Abstract



A method for selectively tuning the wavelength of optical cavities in semiconductor lasers and detectors after epitaxial growth using lateral wet oxidation. Tuning layers of $Al_xGa_{1-x}As$ and $Al_yGa_{1-y}As$ are positioned inside or adjacent to the optical cavity. Wet lateral oxidation is then used to transform the high-index semiconductor into a low-index oxide for tuning. The oxidation proceeds laterally into the $Al_xGa_{1-x}As$ and then attacks the $Al_yGa_{1-y}As$ layer vertically. The ratios of the oxidation rates can be controlled by adjusting the compositions of the materials, most notably because the oxidation rate increases as the amount of aluminum increases. The oxidized thickness depends on the time that the tuning layer is exposed to vertical oxidation. Due to the change in optical index from the semiconductor to the oxide, the optical thickness and the resonant wavelength of the cavity are also tailored along the lateral oxidation. As a result, the resonant wavelength of a device depends on its distance from the etched edge.

TITLE OF THE INVENTION

POSTGROWTH ADJUSTMENT OF CAVITY SPECTRUM FOR SEMICONDUCTOR LASERS AND DETECTORS

RELATED APPLICATIONS

This application claims the priority benefit of co-pending United States Provisional Patent Application 60/083,293 filed April 28, 1998.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support under Grant No. F4960-96-1-0342, awarded by the Air Force Office of Scientific Research. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention pertains to postgrowth adjustment of cavity spectrum for semiconductor lasers and detectors.

2. Description of Related Art

Densely-packed, multiple-wavelength arrays of lasers and detectors are of great interest for telecommunication and computing applications. By encoding N different signals with N different wavelengths (wavelength division multiplexing), the optical fiber can carry N times more information. These arrays are made of vertical-cavity lasers (VCL) and detectors (VCD) which emit or receive light perpendicular to the wafer, so that a two-dimensional array of devices can be easily integrated on the wafer. The single devices are typically made of an active gain or absorbing material embedded in an optical cavity between two semiconductor or oxide Bragg mirrors. The resonant wavelength of the device is determined by the optical length of the cavity, since the gain and absorption bandwidths are usually smaller than the cavity free spectral range. Thus, to change the operational wavelength and fabricate a multiple-wavelength array, it is necessary to change the cavity thickness. This usually requires accessing to the cavity from the surface and selectively etching or oxidizing on the different devices of the array. A second epitaxial growth is then required for the upper Bragg mirror, which complicates the device processing. Another approach is to tailor the cavity thickness on the wafer by growing on patterned substrates. However, this implies an unconventional

growth technique. However, these two approaches are not suitable for massive device production, due to complicated processing and high cost.

SUMMARY OF THE INVENTION

The present invention generally pertains to a technique to change the resonant wavelength of optical cavities used in surface-emitting lasers and resonant detectors after the epitaxial growth, as well as the resultant devices. These devices are made of a semiconductor optical cavity embedded between two semiconductor Bragg mirrors.

By way of example, and not limitation, in the present invention we use lateral wet oxidation of a high Al-content $Al_xGa_{1-x}As$ layer adjacent to the cavity to provide access to the optical cavity after growth. The wet oxidation first proceeds laterally into the $Al_xGa_{1-x}As$ layer, then vertically into an $Al_yGa_{1-y}As$ ($y<x$) layer inside the cavity. Due to the different refractive indices of the oxide and the semiconductor, this changes the optical length of the cavity, hence the resonant wavelength. In this postgrowth process, regrowth of the top mirror is no longer necessary.

Arrays of devices with different resonant wavelengths can be realized by tailoring the etched pattern for the lateral oxidation. The wavelength spacing between the devices can be designed by optimizing the thickness and composition of the layers and the oxidation conditions. A coupled-cavity scheme can also be used to optimize the wavelength spacing. The wavelength span in the array can be maximized by using high-contrast, partially or totally oxidized mirrors. This technique allows the realization of multiple-wavelength, densely packed lasers and detector arrays with a simple postgrowth processing.

DESCRIPTION OF THE DRAWINGS

The invention will be more fully understood by reference to the following drawings which are for illustrative purposes only:

FIG. 1 is a schematic side-view of a multiple-wavelength array of lasers or detectors. A layer of $Al_xGa_{1-x}As$ ($x\approx1$) is laterally oxidized from the etched edge and supplies the reactants for the vertical oxidation of the $Al_yGa_{1-y}As$ ($0.5<y<0.95$) tuning layers. A tapered profile is thus naturally formed.

FIG. 2A through FIG. 2B are top views of different geometries for linear multiple-wavelength arrays. In FIG. 2A the devices are aligned along the lateral oxidation direction. In FIG. 2B the wavelength spacing depends on the

angle between the array axis and the lateral oxidation direction. In FIG. 2C oxidation of each device is controlled separately. The FIGURE is not to scale.

FIG. 3 is a schematic top-view of a bi-dimensional multiple-wavelength array of devices. Oxidation of each device starts from a separate etched edge, so that each wavelength can be controlled separately.

FIG. 4 is a schematic side-view of a coupled-cavity tunable cavity. The tuning layer and the active region are separated by a spacer (i.e., one or more mirror periods), resulting in a smaller variation of resonant wavelength as a function of oxidized thickness.

FIG. 5 is a graph showing characteristics of a multiple-wavelength, top-emitting VCL structure with semiconductor/oxide mirrors and two intracavity contacts. The thin line represents the refractive index, and the thick line represents electric field intensity at 980 nm. The tuning layer is composed of an AlAs layer which is laterally oxidized ("OX") and a $Al_{0.7}Ga_{0.3}As$ ("70%") which is progressively transformed into oxide.

FIG. 6 is a graph showing the calculated resonant wavelength for the cavity shown depicted in FIG. 5, as a function of the thickness of $Al_{0.7}Ga_{0.3}As$ transformed into oxide.

FIG. 7 is a graph showing the calculated threshold gain (continuous line) and external differential efficiency (dashed line) for the VCL structure depicted in FIG. 5, as a function of emission wavelength.

DETAILED DESCRIPTION OF THE INVENTION

Referring more specifically to the drawings, for illustrative purposes the present invention is described with reference to FIG. 1 through FIG. 7. It will be appreciated that the apparatus of the invention may vary as to configuration and as to details of the parts and that the method of the invention may vary as to the specific steps and their sequence without departing from the basic concepts as disclosed herein.

The present invention provides a technique to tailor the optical thickness of the cavity without removing the top mirror or using unconventional growth techniques, and is particularly well suited to multi-wavelength, multi-cavity arrays. A schematic of an exemplary device array 10 is shown in FIG. 1. One or more layers 12 of $Al_xGa_{1-x}As$ ($x \approx 1$) are positioned inside the cavity or next to it. Adjacent layers 14 of $Al_yGa_{1-y}As$ ($0.5<y<0.95$) constitute the "tuning layers". Wet oxidation is used to transform the high-index semiconductor (the refractive index, "n", of AlGaAs is in the range from 3.0 to 3.5) into a low-index oxide (the refractive index, "n", of $Al_2O_3 \approx 1.6$). The wet oxidation is typically

performed in an oven at 400-500°C in a water-vapor atmosphere. The oxidation rate of $Al_xGa_{1-x}As$ layers depends strongly on the Al-composition and temperature, with increasing rates for high x and high temperatures. The oxidation first proceeds laterally from an etched surface 16 near to the device. Due to the composition difference (x>y), the $Al_xGa_{1-x}As$ layers oxidize laterally faster than the $Al_yGa_{1-y}As$ layers. By choosing the two compositions x and y, the ratio of the two oxidation rates can be varied between 1 and $<10^{-4}$. For example, with x = 1 and y = 0.7, the $Al_xGa_{1-x}As$ oxidizes approximately equal to one thousand times faster than the $Al_yGa_{1-y}As$. In these conditions, the oxidation first proceeds laterally into the $Al_xGa_{1-x}As$ layer, then attacks the $Al_yGa_{1-y}As$ layer vertically. The oxidized thickness depends on the time the tuning layer is exposed to vertical oxidation, therefore on the distance from the etched edge. Due to the change in the optical index from the semiconductor to the oxide, the optical thickness and the resonant wavelength of the cavity is also tailored along the lateral oxidation direction. The resonant wavelength of a device then depends on its distance from the etched edge.

Different geometries can be used to realize multiple-wavelength arrays. One possibility is to place the different devices in the array at different distances from a common etched edge. FIG. 2A shows a linear array based on this principle. The wavelength spacing between the devices in this case depends on the distance between them, on the ratio of the oxidation rates and on the position of the tuning layers in the cavity. The oxidation rates can in turn be optimized by varying the Al-compositions, the layer thicknesses and the oxidation temperature. One more degree of freedom can be gained by varying the form and position of the etched edge with respect to the devices. As an example, FIG. 2B and FIG. 2C show two geometries to vary the wavelength spacing in a linear array. Similar approaches can be applied to bi-dimensional arrays. A different approach is to provide a separate etched edge for each device, as shown in FIG. 3. In this case, the resonant wavelength of each device can be controlled separately, still keeping a single oxidation step.

The wavelength spacing between the devices also depends on the cavity structure. The variation of the resonant wavelength as a function of the oxidized thickness can be optimized by choosing the position of the tuning layer in the cavity. This variation is less pronounced if the tuning layer is positioned a few mirror periods away from the cavity, in the coupled cavity scheme shown in FIG. 4. This can help in achieving a good control and reproducibility of the resonant wavelength.

The total wavelength span in the array is mainly limited by the bandwidth of the Bragg mirrors. This happens because increased transmission near to the mirror bandwidth edge reduces the cavity finesse, hence implies higher threshold gains for lasers, etc. To optimize the wavelength span, it is thus desirable to use mirrors with high index contrast. $GaAs/Al_2O_3$ mirrors obtained by selective lateral oxidation present a large index contrast ($n(GaAs) - n(Al_2O_3) \approx 1.9$) and a wide bandwidth. Moreover, oxidation of the mirrors is compatible with the oxidation of the tuning layer and can take place in the same oxidation step.

As an example, FIG. 5 shows the cavity structure (refractive index and electric field intensity at resonance) for a multiple-wavelength top-emitting VCL using a tuning layer one mirror period away from the cavity, semiconductor/oxide mirrors and two intracavity contacts. The $Al_{0.7}Ga_{0.3}As$ tuning layer (244 nm thick) is oxidized from the adjacent AlAs (73 nm thick) layer. FIG. 6 shows the resonant wavelength for this structure as a function of the thickness of $Al_{0.7}Ga_{0.3}As$ transformed into oxide. The total wavelength span is 66 nm around the central wavelength of 980 nm. FIG. 7 shows the calculated threshold gain and external differential efficiency as a function of wavelength. Due to the wide bandwidth of the mirrors, the threshold gain and the differential efficiency vary by only 30% and 20% respectively over the 66 nm wavelength span.

Another advantage of this technology is that slight tapering of the oxidized thickness inside the cavity can produce a lens-like focusing effect. This may be used to reduce optical loss and/or to induce polarization selectivity. For instance, the oxidation patterning schemes shown in FIG. 2B and FIG. 2C break the in-plane isotropy and provide polarization selectivity.

It should also be understood that this technology can be applied to other devices, whenever a change in the thickness of a layer is desirable. Other examples include varying the capacitance of a semiconductor (metal)/oxide/semiconductor capacitor, or varying the effective index in a waveguide. For instance, all photonic integrated devices using resonant effects, as interferometers, filters, etc., can be tuned by oxidation. Also, the phase-matching wavelength in guided-wave frequency converters can be significantly changed by this technique, providing a much wider tuning range.

Accordingly, it will be seen that this invention provides a method for selectively tuning the wavelength of optical cavities in semiconductor lasers and detectors after epitaxial growth using lateral wet oxidation. Although the description above contains many specificities, these should not be construed

as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention.

The invention claimed is:

1. A method for tuning a resonant wavelength of an optical cavity in a semiconductor device, comprising the steps of:

positioning high-index semiconductor layers within said optical cavity;

transforming said high-index semiconductor layers into low-index oxide layers by applying wet lateral oxidation for a duration; and

controlling said duration to determine said resonant wavelength.

2. The method of claim 1, wherein:

said low-index oxide layers have a resultant vertical dimension; and

said resultant vertical dimension depends on said duration.

3. In a semiconductor device that includes an array of optical cavities, a method for tuning a resonant wavelength of each optical cavity, comprising the steps of:

positioning high-index semiconductor layers within said semiconductor device, spanning said array of optical cavities from an etched edge of said semiconductor device to a distant edge of said semiconductor device;

wherein said high-index semiconductor layers have an initial vertical dimension, and said high-index semiconductor layers taper from said etched edge to said distant edge such that said initial vertical dimension at said etched edge is different from said initial vertical dimension at said distant edge;

transforming said high-index semiconductor layers into low-index oxide layers by applying wet lateral oxidation for a duration; and

controlling said duration to determine said resonant wavelength.

4. The method of claim 3, wherein:

said resonant wavelength depends on the distance of the optical cavity from said etched edge.

5. The method of claim 3, wherein:

said low-index oxide layers have a resultant vertical dimension, and

said resultant vertical dimension depends on said duration.

6. A semiconductor device, comprising:

a bottom mirror;

a top mirror;

an optical tuning layer having a vertical dimension;

wherein said vertical dimension determines a resonant wavelength of said semiconductor device.

7. A semiconductor device, comprising:

an array of optical cavities;

wherein said array of optical cavity includes:

a bottom mirror,

a top mirror, and

an optical tuning layer that spans said array of optical cavities from an etched edge of said semiconductor device to a distant edge of said semiconductor device;

wherein said optical tuning layer has a vertical dimension;

wherein said vertical dimension at said etched edge is different from said vertical dimension at said distant edge.

8. The semiconductor device of claim 7, wherein:

each optical cavity has a resonant wavelength, and

said resonant wavelength depends on the distance of the optical cavity from said etched edge.

9. An optical cavity, comprising:

a bottom mirror;

a top mirror;

an optical tuning layer;

wherein the optical tuning layer is used to alter the resonant frequency of the optical resonant cavity; and

wherein the optical tuning layer can be adjusted after said optical cavity has been formed.

10. The optical cavity of claim 9, wherein:

the optical cavity is a vertical cavity surface emitting laser (VCSEL), and the optical tuning layer is used to adjust the emission wavelength of said VCSEL.

11. The optical cavity of claim 9, wherein:

the optical cavity is a resonant photodetector, and the optical tuning layer is used to alter a detector wavelength of said resonant photodetector.

12. The optical cavity of claim 9, wherein:

the optical cavity is a Fabry Perot modulator and the optical tuning layer is used to alter a modulated wavelength of said modulator.

13. The optical cavity of claim 9, wherein:

the optical tuning layer is adjusted using oxidation.

14. The optical cavity of claim 9, wherein:

the optical tuning layer is adjusted using selective etching.

15. The optical cavity of claim 9, wherein:

the optical tuning layer is adjusted using selective etching followed by back filling with another material.

16. The optical cavity of claim 9, wherein:

the optical tuning layer is made from at least two layers with different oxidation rates.

17. An array of optical cavities according to claim 9.

18. An array of optical cavities according to claim 10.

19. An array of optical cavities according to claim 11.

20. An array of optical cavities according to claim 12.

21. An array of optical cavities according to claim 9, wherein:

each optical cavity is tuned to a different resonant wavelength.

22. An array of optical cavities according to claim 10, wherein:

each VCSEL is tuned to a different emission wavelength, thereby making a wavelength division multiplexed (WDM) array.

23. An array of optical cavities according to claim 11, wherein:

each resonant photodetector is tuned to a different resonant wavelength.

24. An array of optical cavities according to claim 12, wherein: each modulator is tuned to a different resonant wavelength.

25. An optical cavity according to claim 10, wherein: the optical tuning layer is adjusted in an anisotropic manner for polarization control of the VCSEL emission.

26. A resonant-cavity structure for optical waves, comprising: two reflecting elements; a tuning layer; wherein said two reflecting elements and said tuning layer are formed as a multiple-layer stack on a substrate; wherein optical properties of said tuning layer can be altered after the multi-layer stack is formed in order to adjust a resonant wavelength of said resonant-cavity structure.

27. The structure of claim 26, wherein: said tuning layer comprises an alloy that contains aluminum.

28. The structure of claim 27, wherein: said alloy is selected from the group consisting of AlGaAs, AlInAs, AlGaInAs, AlGaP, AlInP and AlGaN.

29. The structure of claim 28, wherein: said alloy can be altered by a lateral oxidation process from an access slot formed in the multiple-layer stack to access said tuning layer.

30. The structure of claim 29, wherein: the composition of said tuning layer is varied vertically by changing the fraction of aluminum across said tuning layer, such that the oxidation process results in a tapered thickness as a function of lateral distance from said access slot.

31. The structure of claim 30, wherein: said access slot forms a straight edge along said tuning layer.

32. The structure of claim 30, wherein: said access slot forms a wedge-shape along said tuning layer.

33. The structure of claim 30, wherein:

said access slot forms a shape along said tuning layer, wherein said shape is selected from the group consisting of circular and elliptical.

34. The structure of claim 26, wherein:

at least one of said two reflecting elements includes a number of layers with differing indexes of refraction, wherein the layers are materials selected from the group consisting of semiconductor and dielectric.

35. The structure of claim 26, wherein:

one of said two reflecting elements is a top surface of said multiple-layer stack.

36. The structure of claim 26, wherein:

said substrate is a semiconductor material selected from the group consisting of GaAs, InP, GaN, AlN, GaSb, Si and SiN.

37. The structure of claim 36, wherein:

at least one of said two reflecting elements includes multiple semiconductor layers with differing indexes that are approximately lattice matched to said substrate.

38. The structure of claim 30, wherein:

at least one of said two reflecting elements includes a number of layers with differing indexes of refraction, wherein the layers are materials selected from the group consisting of semiconductor and dielectric.

39. The structure of claim 30, wherein:

one of said two reflecting elements is a top surface of said multiple-layer stack.

40. The structure of claim 30, wherein:

said substrate is a semiconductor material selected from the group consisting of GaAs, InP, GaN, AlN, GaSb, Si and SiN.

41. The structure of claim 40, wherein:

at least one of said two reflecting elements includes multiple semiconductor layers with differing indexes that are approximately lattice matched to said substrate.

42. The structure of claim 40, wherein:

said tuning layer includes materials that are approximately lattice matched to said substrate.

43. A resonant-cavity structure for optical waves, comprising:

two reflecting elements;

an active layer; and

a tuning layer;

wherein said two reflecting elements, said active layer and said tuning layer are formed as a multiple-layer stack on a substrate;

wherein optical properties of said tuning layer can be altered after the multiple-layer stack is formed in order to adjust a resonant wavelength of said resonant-cavity structure.

44. The structure of claim 43, wherein:

said active layer absorbs light and generates a photocurrent, and further comprising

a contact to said active layer collecting said photocurrent,

wherein said resonant-cavity structure is a wavelength-tunable resonant-cavity photodetector.

45. The structure of claim 43, wherein:

said active layer generates light, and further comprising

a contact to said active layer injecting a pumping current,

wherein said resonant-cavity structure is a wavelength-tunable vertical cavity LED.

46. The structure of claim 43, wherein:

said active layer amplifies light, and further comprising

a contact to said active layer injecting a pumping current,

wherein said resonant-cavity structure is a wavelength-tunable vertical cavity laser.

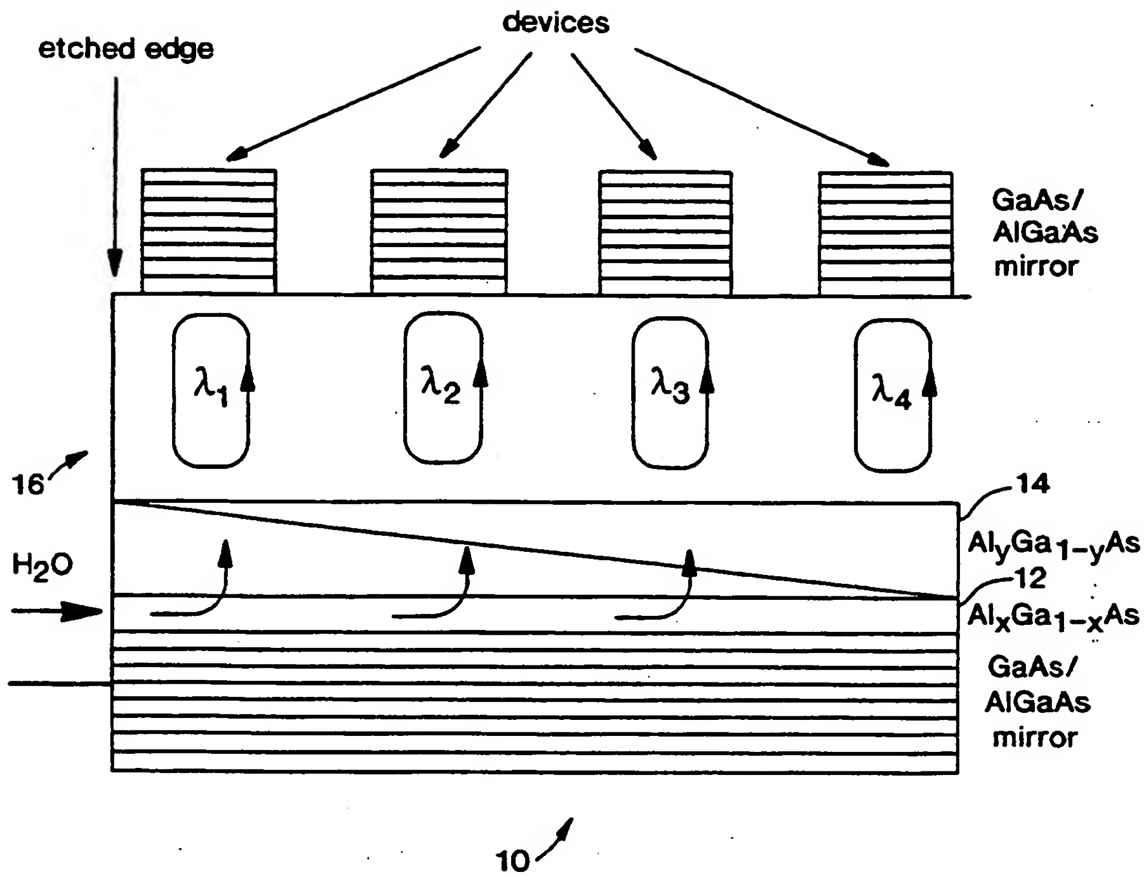

devices
etched edge
GaAs/
AlGaAs
mirror
λ_1
λ_2
λ_3
λ_4
16
14
$Al_yGa_{1-y}As$
H_2O
12
$Al_xGa_{1-x}As$
GaAs/
AlGaAs
mirror
10

FIG. 1

FIG. 2A

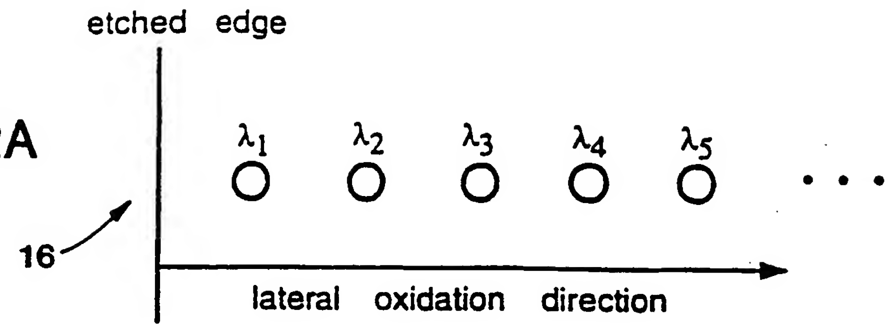


FIG. 2B

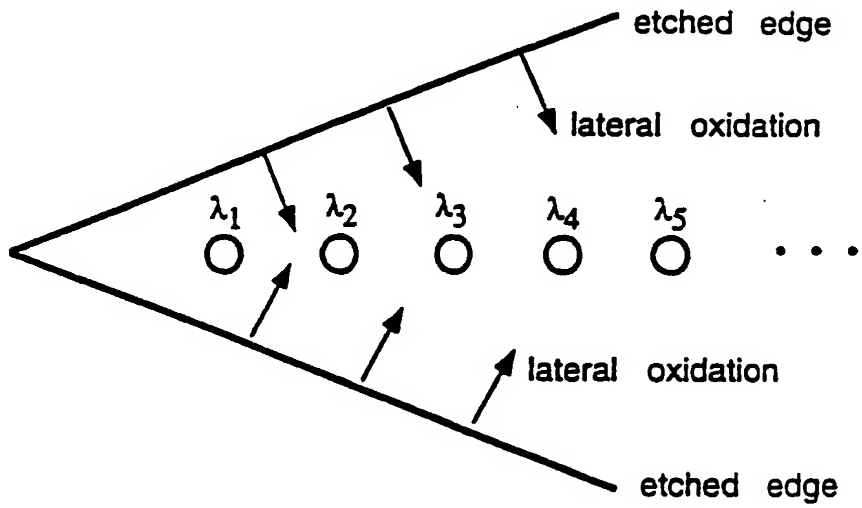
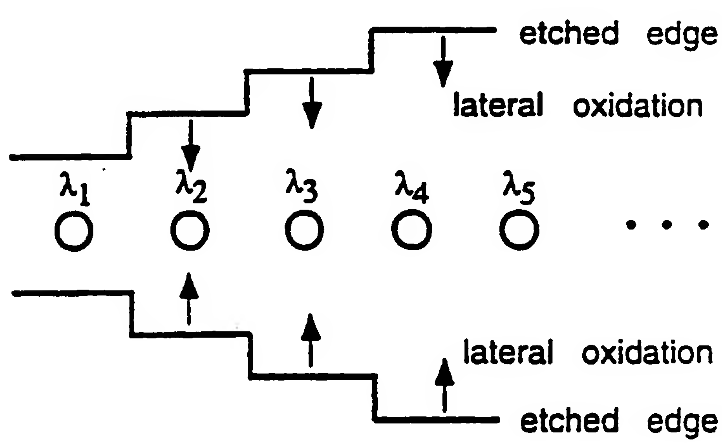


FIG. 2C



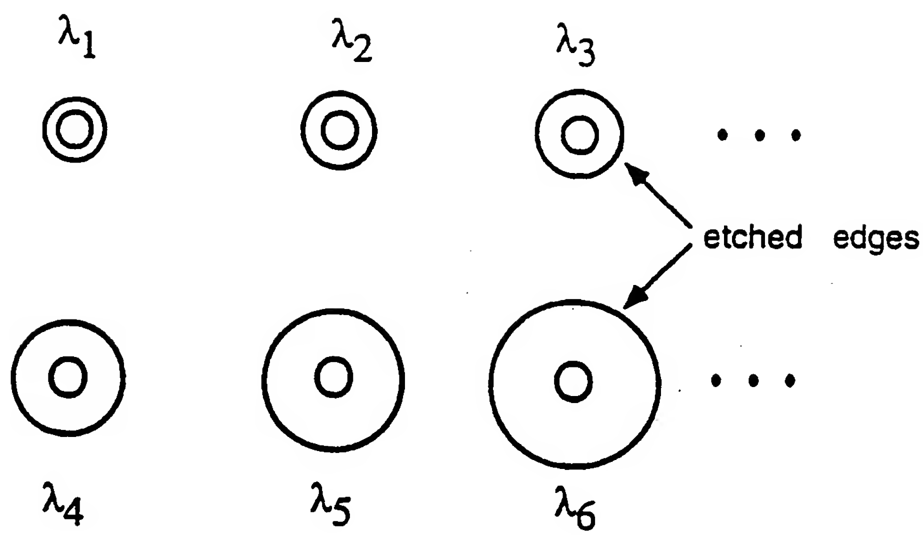

λ_1
λ_2
λ_3
etched edges
λ_4
λ_5
λ_6

FIG. 3

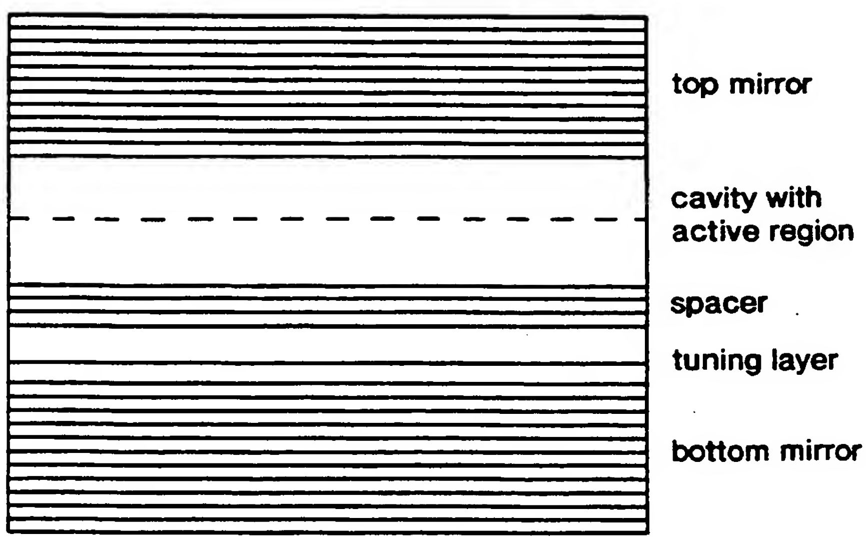

top mirror
cavity with active region
spacer
tuning layer
bottom mirror

FIG. 4

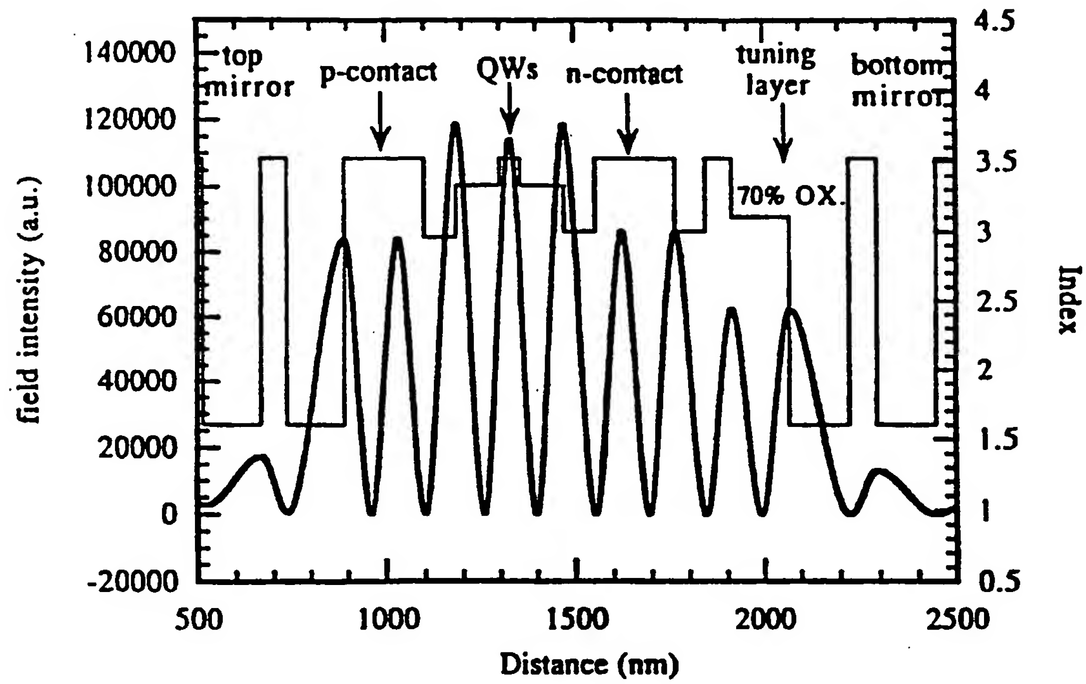

140000
120000
100000
80000
60000
40000
20000
0
-20000
field intensity (a.u.)
top mirror
p-contact
QWs
n-contact
tuning layer
bottom mirror
70% OX.
4.5
4
3.5
3
2.5
2
1.5
1
0.5
Index
500
1000
1500
2000
2500
Distance (nm)

FIG. 5

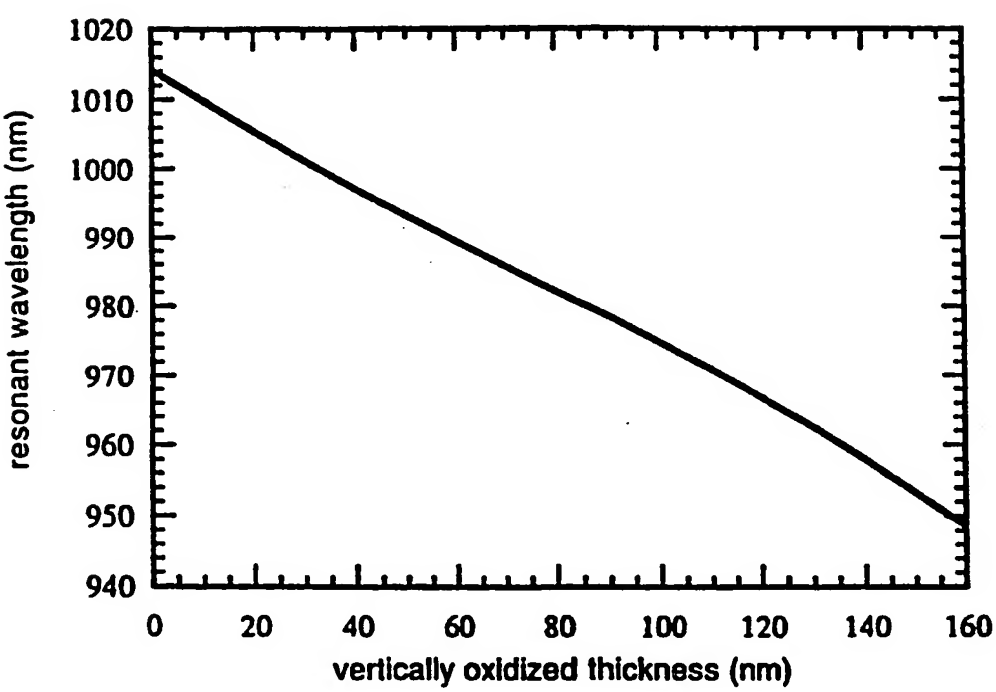

1020
1010
1000
990
980
970
960
950
940
resonant wavelength (nm)
0
20
40
60
80
100
120
140
160
vertically oxidized thickness (nm)

FIG. 6

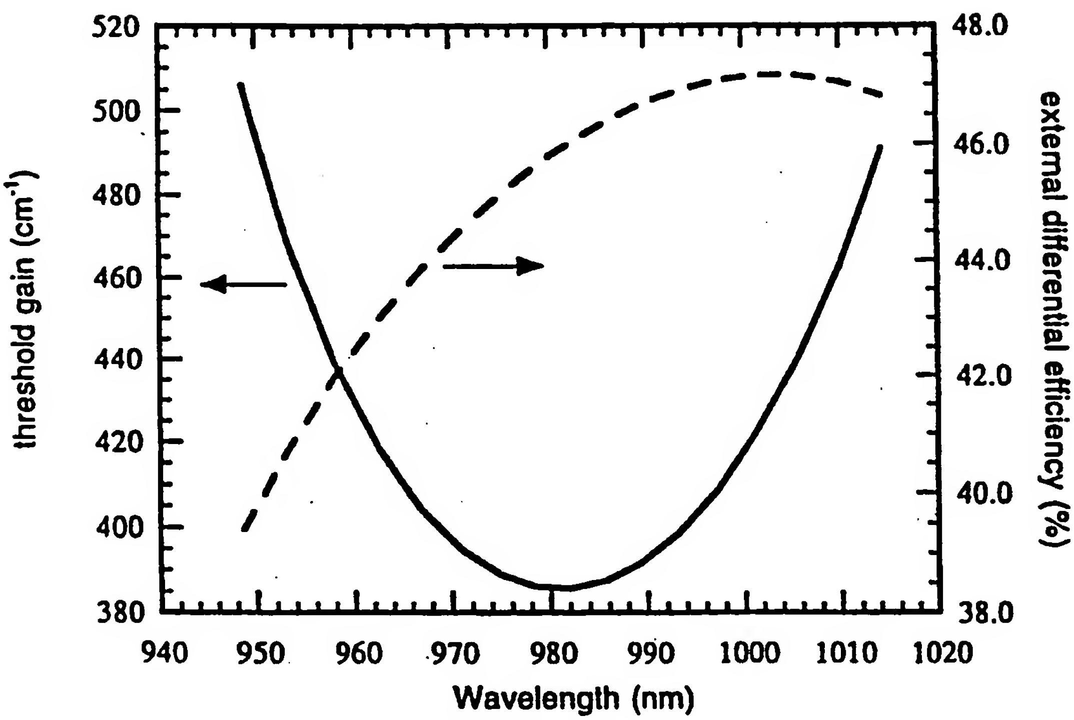

520
500
480
460
440
420
400
380
threshold gain (cm^{-1})
48.0
46.0
44.0
42.0
40.0
38.0
external differential efficiency (%)
940
950
960
970
980
990
1000
1010
1020
Wavelength (nm)

FIG. 7